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# Autonomous Photovoltaic LED Urban Street Lighting: Technical, Economic, and Social Viability Analysis Based on a Case Study

Rami David Orejon-Sanchez , Jose Ramon Andres-Diaz  and Alfonso Gago-Calderon \* 

Proyectos de Ingeniería, Departamento de Expresión Gráfica Diseño y Proyectos, Universidad de Málaga, 29071 Málaga, Spain; rami@uma.es (R.D.O.-S.); jrاندres@uma.es (J.R.A.-D.)

\* Correspondence: agago@uma.es; Tel.: +34-951-952-268

**Abstract:** This paper analyzes the technical and economic viability and sustainability of urban street lighting installation projects using equipment powered by photovoltaic (PV) energy. First, a description of the state-of-the-art of the technology is performed, studying the components involved in solar LED luminaires for street lighting application and examples of autonomous PV systems installed in different countries. Later, a case study based on a renovation project of the street lighting installation at a 5000-inhabitant municipality in Lanzarote (Spain) is presented. Two alternatives are analyzed: underground channeling of the previous aerial electrical grid and the installation of LED luminaires, and, on the other hand, the installation of autonomous LED solar luminaires. Simulations concluded that a PV lighting installation proposal guarantees the existing M3 lighting requirements (EN 13201-2:2015) and represents a saving in the material execution budget of 43.78% with respect to the channeled power grid option. Finally, a statistical study has been carried out to assess the social acceptance of Spanish citizens of this autonomous PV technology in urban environments. This considers strengths and weakness of the technology: sustainability, robustness, visual impact, or risk of vandalism. In general, most subjects of all age segments are aware of the problem that means having aerial wiring running at facades (95%) and considers the use of PV in urban lighting sustainable (88%). However, 47% of those surveyed consider that shutdowns due to lack of energy harvesting is problematic and 17% consider this very problematic. This major drawback (visual impact of PV equipment is mostly evaluated as neutral) gives rise to social reluctance, especially in people younger than 50 who remarked this as more problematic than senior segments. Thus, guaranteed operational service is fundamental to have social agreement for PV technology implementation.

**Keywords:** public street lighting; photovoltaic lighting; smart luminaries; economic viability; underground facilities



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## 1. Introduction

Currently, 1.3 bn people (20% of the world population) do not have access to a distribution grid of electricity at home. This is especially significant in Sub-Saharan Africa (close to 70%), where more than 620 million people live without access to electricity [1]—this is twice the population of the entire USA [2]. Access to energy is a precondition for humans and economic development and can be equated to the limitation of access to food, drinking water, or medicine [3]. Unavailability of electricity grid is a major challenge faced by most developing countries, particularly populations in rural areas [4]. Therefore, using a technology powered by renewable energy contributes to sustainable development, as it reduces energy dependence in an energy system dominated by fossil fuels [5,6]. In this context, Solar Photovoltaic (PV) energy is considered one of the most promising markets in the portfolio of renewable energies [7].

In the 1960s, the first PV luminaires were developed to solve the lighting requirements in places without access to the electricity grid. Commercial development of PV formerly used fluorescence compact lamps as a light source [8]. Currently, the predominant light source is the technology based on light-emitting diodes (LED) [9,10]. LED has become the last major milestone in this sector due to its advantages in energy savings; reliability and electronic control; and, according to one Technical Report of the European Commission, this technology “has turned into a game changer beating conventional technologies on all aspects. It is therefore anticipated that in the short term, all electric lighting will be based on SSLs.” [11]. The digital nature of these new transmitters allows, as a relevant feature, the power supply in direct current (DC) and very low-voltage conditions, which in many cases, can be classified within the Safety Extra-Low Voltage (SELV) working below 30 V<sub>DC</sub> (EN 61,558 standard) [12–15].

In the present paper, several mechanisms to enhance the acceptability of Autonomous Solar-powered Lighting (ASL) equipment in urban context are investigated. First, in Chapter 2, a review of the state-of-the-art of the products developed under this premise is presented including a description of several significant implementation examples worldwide. Then, more in depth, further development of improved ASL installations from technical, economic, and social points of view is presented. Specifically, the technical viability of the solution has been analyzed, verifying the adaptation viability of ASL to the requirements (EN 13201 standards) of a recurrent, real urban public lighting project (M3 or higher—EN 13201-2:2015), used as reference, beyond rural or low requirement class locations. Secondly, economic comparison of the budgets needed to develop the same new installation of the project of reference with (a) underground channeling and civil works to use an alternating current (AC) grid powered solution and (b) ASL single poles that, from the construction point of view, only require the generation of the foundation slabs that sustain the light poles. The analysis of several public tender budgets in Spain related to projects and alike to our purpose and public databases of construction prices have been used for this study. Finally, the general perception of citizens associated with the ASL technology and the impact of its implementation within an urban environment have been questioned and the major results are presented. This information can be used by local authorities and technicians to promote the development of this type of facility adequately in their areas of influence.

## 2. State of the Art

### 2.1. Lighting

Currently, 21% of globally produced electricity is consumed by lighting—18% is due to indoor and 3% to outdoor lighting [16]. In Europe, it is estimated that cities and towns assign, on average, 40% of their budget to cover the energy expenditure associated with indoor and outdoor public lighting [17].

A study performed by the European Commission has shown that between 30% and 50% of electricity used for lighting could be saved by investing in energy-efficient lighting systems [18]. In Spain, in some municipalities, the consumption of energy in public lighting reaches up to 80% of the total electricity consumption. The average power per luminaire in Spain is 157 W. This is one of the highest values found in the European Union, above those found in the United Kingdom (76 W/per luminaire) or The Netherlands (61 W/luminaire) [19,20]. The electronic nature of LEDs is one important reason that makes this technology stand out over other lighting technologies [12]. Such a feature has allowed it to achieve high values of energy efficiency and lifespan, reaching 200 lm/W for equipment in laboratory tests [21] and 100,000 h of life on the emitters, respectively; Table 1 illustrates a comparison of the lifespan and efficacy of various existing lighting technologies [16,22,23].

**Table 1.** Lifespan and average efficiency summary of light source technologies [16,22,23].

Lighting System	Lifespan	Efficacy
Incandescence		
Incandescent	1000 h	12–18 lm/W
Halogen	2000 h	18–22 lm/W
Gas discharge		
Low pressure mercury vapor	5000–15,000 h	38–91 lm/W
High pressure mercury vapor	8000 h	40–60 lm/W
Blended lamp	6000 h	20–60 lm/W
Metal halide	9000 h	60–95 lm/W
Low pressure sodium vapor	6000–8000 h	160–180 lm/W
High pressure sodium vapor	8000–12,000 h	130 lm/W
Compact fluorescent lamp	8000 h	60 lm/W
Plasma		
Plasma	30,000 h	85 lm/W
Solid-state lighting		
LED	50,000–100,000 h	80–300 lm/W

Moreover, the advantages of LED lighting are not limited to the fields of energy efficiency and lifetime expectancy. Light quality based on visual parameters such as chromaticity or color rendering affect significantly on user acceptability of lighting technologies, i.e., early compact fluorescent lamps suffered upon market introduction due to their poor color rendering and appearance [24]. LED phosphor-converted (PC) white light performance and its continuous development is improving in new packages, in a combined way and within a wide range of correlated color temperature (CCT), the Duv, and color rendering metrics, such as AN-SI/IES TM-30 or CRI Ra [25,26]. Nowadays, even cool white light is available with CRIs higher than 90 as red-light conversions are being improved using, for example, co-doped phosphor-in-glass (PiG) [27].

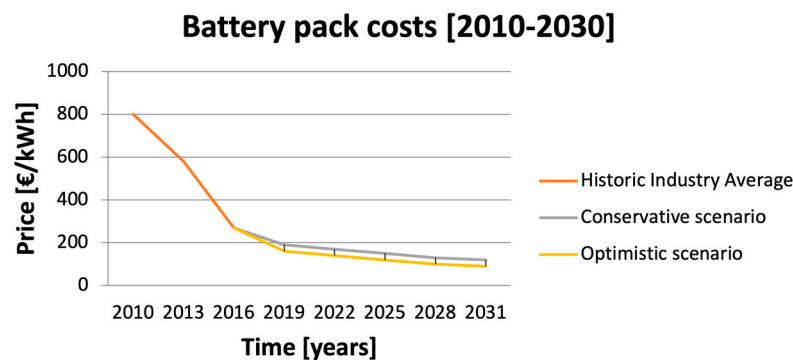
## 2.2. Photovoltaic Energy Generators

Due to the increased production of photovoltaic panels in China, the cost of these elements has decreased. This has boosted the usage of such energy with respect to other renewable energies due to new competitive prices. The growth of installed power of global PV energy increases between 20–25% every year [28–31].

Since 2015, China has become the nation with the greatest installed capacity of PV. In 2016, global polysilicon production continued to rise with an increase of 12.6% from 2014 (China produces 48.5% of the world's total amount), similarly to PV modules production, with an increase of 15.4% [32,33].

## 2.3. Energy Storage Technologies: Batteries

The use and development of batteries represents one of the basic elements for a change in energy model. They are essential tools for the development of strategic sectors such as electric vehicles (approximately, every five years, the global demand of rechargeable Lithium-Ion Batteries growth has multiplied by two) [34] or to settle permanently the photovoltaic panels and the rest of renewable sources as the main segment of the energy mix [35,36]. It is noteworthy that, as per the International Energy Agency (IEA) records, since 2008, the cost of batteries has divided by four, while the energy storing density has multiplied by five [37–39]. Li-ion batteries are the technology of choice for energy storage by virtue of their technical and economic advantages, including an annual decline in manufacturing costs of 10% to 15%. Nowadays, it costs about 270.00 €/kWh to produce a Li-ion battery pack and Figure 1 shows the expected trend in the price of batteries [40].



**Figure 1.** Expected trend in the price of batteries from 2010 to 2030 [40].

#### 2.4. Regulations and Recommendations for Urban Lighting

The level of illumination required by each type of street depends on multiple factors such as the complexity of its setup, intensity of traffic, maximum speed, and traffic control systems or the separation between lanes for different types of users [41].

The Commission Internationale de l’Eclairage (CIE) describes two types of road lighting classes: the first one includes all road users—operators of motor vehicles, motorcycles, pedal cycles, and animal-drawn vehicles; the second class is for pedestrians [42]. The CIE is based on a new weighting concept for the selection of lighting classes (M1–M6) [43,44]. On the other hand, the European standard EN 13201-2: 2015 “Road lighting—Part 2: Performance requirements” presents two types of recommendations, the M-classes and the P-classes. The M-class is intended for drivers and the P-class for pedestrians, cyclists, and low-speed drivers (<40 km/h). In North America, the basis of the Illuminating Engineering Society of North America’s road lighting recommendations, developed in 1972, are still the basis of current standards [39,40].

In Spain, the national regulation framework develops the criteria based on the CIE and the Illuminating Engineering Society (IES) [45], as the classification of road types is established according to their lighting requirements. On the basis of previous criteria, routes of circulation are classified into several groups or project situations, assigning to each one of them specific photometric requirements that take into account the visual needs of the users as well as environmental aspects. One of the most important criteria when classifying roads is the speed of traffic for each, which is established in Table 2. However, it is necessary not only to replace the old luminaires (mostly high-pressure sodium) with LED luminaires, but to study the regulation of the lighting levels since the photometric curve of LED luminaires can be completely different [43].

**Table 2.** Road classification according to vehicle speed [45].

Classification	Type of Road	Speed of Road Traffic (km/h)
A	high speed	$v > 60$
B	moderate speed	$30 < v < 60$
C	bicycle lane	–
D	low speed	$5 < v < 30$
E	pedestrian path	$v < 5$

On the other hand, in relation to energy efficiency there are energy performance indicators for road lighting. In the European standard, the Power Density Indicator (PDI) and the Annual Energy Consumption Indicator (AECI) have been defined [46]. Energy performance in PDI is expressed as the consumed electrical system power for the maintained average horizontal illuminance per square meter ( $W/(lx \cdot m^2)$ ) [47]. AECI is the annual energy consumption for a road lighting installation ( $Wh \cdot m^{-2}$ ), this indicator states the electrical energy consumption for a road lighting system during the year, also taking into account specific night-time or seasonal lighting performance [48].

## 2.5. Examples

### 2.5.1. Cuimba, Angola

In the context of this research, we participated in a public lighting project consisting of 1365 autonomous 50 W LED lights in the city of Cuimba (Angola), as illustrated in Figure 2. The budget to install this type of lighting equipment was reduced by more than 35% in comparison with the channeling of the existing electrical grid to install a lighting system connected to the grid.



**Figure 2.** Foundation, installation, and start-up of a PV lighting installation in Cumbia, Angola. Aesthetic differences between ASL (left of the road) and AC grid aerial wires (right of the road).

### 2.5.2. Brisbane, Australia

In a project funded by the University of Queensland (Brisbane), the option of replacing the lighting system of the city with LED solar luminaires was determined as viable for this type of location [49].

### 2.5.3. Jordan

In an economic feasibility study developed by Al-Kurdi et al. [50], which investigates the possibility of using LED solar lighting systems in public lighting for roads in Jordan, it was determined that savings of 50% were obtained with respect to the currently existing installation. In reference to the amortization periods, the following results were obtained:

- Payback period of 7.20 years for AC grid powered LED lighting installations.
- Payback period of 3.15 years for LED ASL lighting installation.

### 2.5.4. Indonesia

Mardikaningsih et al. [51] carried out a technical–economic feasibility study using methods such as the net present value or the cost–benefit ratio with a projection to 25 years. They determined that the investment was feasible using solar street lighting luminaires. The profitability was 97% higher than using the supply network. Moreover, the energy mix of the actual power grid consisted mainly of fossil fuels production.

## 3. Methods

In order to analyze the technical viability of ASL implementation within typical urban streets regulation requirements and to perform an economic comparison of the budgets needed to conclude the same installation with AC grid powered luminaires and ASL, we used, as a case study, the following real project. In the municipality of Haría (Las Palmas, Spain; latitude: 29°8'47" North), in 2018, the public tender “Renovation of the public lighting of the town of Tabayesco” was published (hereinafter reference project, see Figure 3). The project covers the underground channeling of the energy supply as well as the installation of new LED luminaires.



**Figure 3.** Renovation of the public lighting of the town of Tabayesco, Municipality of Haría, Las Palmas, Spain. Photographed in September 2018.

An own research, commissioned by the Haría City Council, presented in April 2018 (expedient number 2017000690), was developed with the aim of carrying out an analysis of the technical–economic feasibility of urban LED solar lighting installations in this municipality. During this period, the aforementioned reference project was analyzed in order to evaluate the viability of solar lighting projects for future public tenders of the municipality. This describes the baseline of the current case study, where the requirements, necessary works, problems, and identifiable costs in the installation of the new ASL lighting are compared to comply with the reference project.

The technological analysis included the sizing of LED lighting installation powered by solar energy able to supply this locality, complying with the lighting requirements set in the reference project.

For the economic analysis, the reference project, the proposed ASL alternative, and the results of a public tenders analysis in Spain to generate street lighting installations using autonomous solar luminaires were compared. As presented, the fulfillment of a specific correlated color temperature (CCT) and a minimum color rendering index (CRI), as indicated in the following chapter, were used to select both luminaires used in the study. More quality-dependent variables, not included in the regulations, could be used in a more specific study, such as the Duv, IES TM-30 Rf, or CRI R9, but the differences in the LED matrixes prices and performance due to these elements would be exactly the same in AC grid power or in ASL cases.

Finally, a statistical study is presented, where the social acceptance of citizens associated with this type of technology in urban environments is analyzed. An open online questionnaire with six items was used. They are related to the esthetic impact of aerial wires channeling or ASLs (which increased largely in size by means of battery boxes and PV panels) and the acceptance of the possibility of shutdowns of light due to lack of energy harvesting or vandalism. No specific aspects related to light quality were included as they cannot be presented an equal luminaire of reference or installation to all the participants. Data were analyzed using Fisher’s Exact test and the two-proportions z-test with IBM SPSS Statistics (version 25).

#### **4. Study of Technological, Economic, and Social Viability**

##### *4.1. Analysis of Technical Viability: Case Study*

##### **4.1.1. Problem Description**

As a result of the deficiencies detected in a previous energy auditory carried out by the Haría City Council, the local public administrations elaborated a plan for the renewal of municipal public lighting. Besides the lighting requirements, this plan proposes the adjustment to the regulations of the electricity supply that provide service to public lighting.

Among these actions, the underground channeling of the power line is contemplated. As can be seen in Figure 4, it is very usual to observe electrical conduction



**Figure 4.** Identification of the problem. Tabayesco, Municipality of Haría, Las Palmas, Spain. Photographed in January 2018.

#### 4.1.2. Sizing of the Luminaires Installation

The region where the study is focused is classified as ‘E1 Zone’, referring to an area with dark environments, intended for astronomical observatories of the international category, national parks, spaces of natural interest, special protection areas (natural network, protection zones of birds, etc.) where roads are not illuminated. This implies specific operating conditions, such as a warm color temperature of the luminaires (3000 K) or a flow to the upper hemisphere ( $FHS_{INST}$ ) less than or equal to 1% of the total emitted. Based on its specific conditions, the street has been classified as M3 (EN 13201-2:2015).

With the mentioned requirements and knowing the geometrical parameters of the street, the power of the luminaires is dimensioned with the open access DIALux software. In the reference project, two types of streets are established, and the results are summarized in Table 3.

**Table 3.** Road classification according to vehicle speed [45].

Street Type	1	2
Street classification (EN 13201-2:2015)	M3	M3
Number of lanes	1	1
Width of the road	7.0 m	6.0 m
Interdistance	18.0 m	21.5 m
Light point height	6.0 m	6.0 m
Poles	5 m of height. Galvanized steel	
Layout	one-sided	one-sided
Power of the luminaires (Reference)	58.1 W	58.1 W
Power of the luminaires (Solar LED)	40.0 W	40.0 W

Luminaire (reference project)

PHILIPS BDP794 FG 108 xGRN70/830 DW  
 N° de artículo:  
 Flujo luminoso (Luminaria): 4969 lm  
 Flujo luminoso (Lámparas): 7099 lm  
 Potencia de las luminarias: 58.1 W  
 Clasificación luminarias según CIE: 100  
 Código CIE Flux: 35 70 96 100 70  
 Lámpara: 108 x GRN70/830/- (Factor de corrección 1.000).

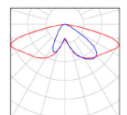
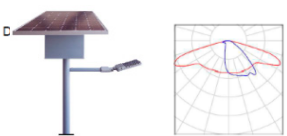


Table 3. Cont.

Street Type	1	2
Luminaire (proposed installation)	Solitec NaviaP DC A NaviaP-DC-40-N-C14145 N° de artículo: A Flujo luminoso (Luminaria): 4535 lm Flujo luminoso (Lámparas): 4815 lm Potencia de las luminarias: 40.0 W Clasificación luminarias según CIE: 100 Código CIE Flux: 98 93 100 94 Lámpara: 1 x CREE XT-E (Factor de corrección 1.000).	

#### 4.1.3. Components and Simulation of the Proposed Installation

Table 4 lists the mathematical framework used to dimension the PV generator of the luminaries and Table 5 summarizes the components that make up the LED solar installation dimensioned for the locality under study. This section summarizes the results of the lighting simulation, 3D modelling, and final rendering (see Figure 5). The 3D rendering model, despite having an apparently esthetic approach, is made to enrich the study of social viability, since it allows respondents to have a three-dimensional projection of the proposed installation. Tables 6 and 7 indicate the planning data used to dimension the luminaires corresponding to the majority of the streets of the municipality and the results obtained related to the class requirements class established the Spanish regulation based on the previously named standard EN 13201-2: 2015. The maintenance factor used in the simulations mean the luminance values measured in the executed installation will be higher and the uniformity may also be increased in the locations where the proximity to houses with almost completely white facades and walls may reflect light back to the road.

Table 4. Equations for dimensioning LED lighting installation powered by solar PV energy.

Photovoltaic Generator	
$P_{G-min} = \frac{W_d \cdot G_{CEM}}{G_{(\alpha,\beta)} \cdot K_T}$	$W_d$ : Energy consumption (Wh/day) $G_{CEM}$ : Standard radiation, 1000 W/m <sup>2</sup> $G_{(\alpha,\beta)}$ : Incident radiation (Wh/m <sup>2</sup> ·day) $K_T$ : Battery and regulator efficiency (%)
Battery	
$C_N = \frac{Q_d \cdot A_u}{PD_{MAX} \cdot \eta_{B+R}}$	$Q_d$ : nominal daily capacity (Ah/day) $A_u$ : Autonomy days $PD_{MAX}$ : Maximum discharge depth $\eta_{B+R}$ : Battery and regulator efficiency
Regulation System	
$U_{OC(Tmin)} = U_{OC} + \beta \cdot (T_{min} - 25)$ $I_R = 1.25 \cdot I_{G,sc}$	$U_{OC(Tmin)}$ : Rated voltage (V) $T_{min}$ : Historical minimum temperature (°C) $U_{OC}$ : open-circuit voltage (V) $I_{G,sc}$ : short-circuit current of the generator (A) $I_R$ : input current to the regulation system (A) $\beta$ : temperature coefficient (mV/°C)

Table 5. Components of the proposed ASL installation (Source: own elaboration). As indicated, several data are presented both as indicated by the manufacturer and measured in a sample unit.

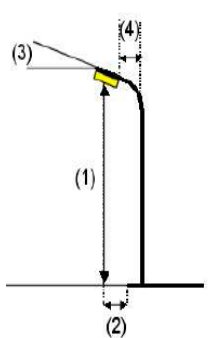
Component	Parameter	Value
Luminaire	Electric power (manufacturer/measured)	40 W/41.1 W
	Luminous flux (nominal)	4535 lm
	CCT (manufacturer/measured)	3000 K/2902 K
	Ingress Protection (manufacturer)	IP66
	Impact resistance (manufacturer)	IK09
	CRI (manufacturer/measured)	>80/81.5
	CRI-R9 (measured)	14.7
	Rf IES-TM-30 (measured)	82.5
Duv (measured)	0.0028	



**Table 5.** *Cont.*

Component	Parameter	Value
Accumulation system (Battery)	Nominal voltage	12 V <sub>DC</sub>
	Capability	2 × 120 (Ah)
	Weight	32.2 kg
	Dimensions (Length × Width × Height)	407 × 173 × 233 mm
Regulation system	Ingress Protection	IP68
	Nominal voltage	12/24 V
	Dimensions (Length × Width × Height)	82 × 100 × 20 mm
	Operating intensity	10 A <sub>DC</sub>
Photovoltaic panel	Weight	0.14 kg
	Nominal electric power	150 W
	Efficiency	15.42%
	Nominal voltage	12 V <sub>DC</sub>
	Dimensions (Length × Width × Height)	1476 × 659 × 35 mm
Pole	Weight	11.9 kg
	Height	5 m
	Material	Galvanized steel

**Table 6.** Planning data, simulation in DIALux (Source: own elaboration).

Street Type	A	B	Scheme of the Installation
Model	NaviaP <sub>DC</sub> 40-N-C <sub>14145</sub>	NaviaP <sub>DC</sub> 40-N-C <sub>14145</sub>	
Power	40.0 W	40.0 W	
Street width	6.0 m	7.0 m	
Transit lanes	1	1	
Organization	one-sided	one-sided	
Maintenance factor	0.85	0.85	
Distance between masts	18.0 m	21.5 m	
(1) Light point height	6.0 m	6.0 m	
(2) Distance on street	-0.5 m	-0.5 m	
(3) Arm tilt (degrees)	0°	0°	
(4) Arm length	0.5 m	0.5 m	




**Figure 5.** Installation of proposed LED solar lighting. (Left) 3D model of the luminaire inserted in Google Earth. (Central) Street view in Google Maps. (Right) 3D model in SketchUp Pro, rendered with Vray (Source: own elaboration).**Table 7.** Luminotechnical results, simulation performed with DiALux (Source: own elaboration).

Street Type	ASL Luminaire A Road (Simulation)	ASL Luminaire B Road (Simulation)
Street classification (EN 13201-2:2015)	M3	M3
Average luminance (Lm)	1.10 cd/m <sup>2</sup> (1.0 cd/m <sup>2</sup> )	0.98 cd/m <sup>2</sup> (1.0 cd/m <sup>2</sup> )
Overall uniformity (U0)	0.43 (≥0.40)	0.47 (≥0.40)
Longitudinal uniformity (UI)	0.80 (≥0.60)	0.92 (≥0.60)
Threshold increment (TI (%))	10 (≤15)	11 (≤15)
Surround ratio (SR)	0.52 (≥50)	0.60 (≥50)

#### 4.2. Analysis of Economic Viability

First, the estimated value of the reference project was set at 326,960.38 €, for a total of 99 LED luminaires. Therefore, the average price per LED luminaire for this project was estimated as 3302.63 €. Tables 8 and 9 summarize the detailed material execution and the general budget, respectively, of the APL alternative to the reference public tender project with the average prices calculated for the necessary elements and equipment [52].

**Table 8.** Material Execution Budget estimation for an APL alternative project.

Chapter	Subchapter	Concept	Amount	Descriptive Image			
Electricity	Luminaires	ASL LED luminaire (Unit)	195.00 €				
		Gel battery 12 V/185 Ah + Protec Box (Unit)	360.00 €				
		Photovoltaic module 150 W/12 V + Fixing (Unit)	178.78 €				
		Solar regulation system (Unit)	68.00 €				
		Electrician officer and assistant and aux means	29.53 €				
		<b>Total item</b>	<b>831.31 €</b>				
<b>Total chapter (99 luminaires/project)</b>				<b>82,300.39 €</b>			
Civil work	Base foundation	Fck (17.5 N/mm <sup>2</sup> ) mass concrete (m <sup>3</sup> )	13.19 €				
		Manual excavation (Unit)	12.93 €				
		Formwork (Unit)	19.50 €				
		Elbow 90 PVC-U D 110 mm (Unit)	3.34 €				
		Construction worker and auxiliary means	5.62 €				
		<b>Total item</b>	<b>54.57 €</b>				
Civil work	Poles	5-m galvanized steel pole with fixing utilities (Unit)	515.00 €				
		6-ton crane truck (h)	34.33 €				
		Electrician officer and assistant and aux means	23.87 €				
		<b>Total item</b>	<b>573.20 €</b>				
		<b>Total chapter (99 luminaires/project)</b>				<b>62,097.45 €</b>	
		Security and health	Traffic signaling and control of access		209.17 €		
Working kit			51.38 €				
Individual protection equipment			366.35 €				
Occupational safety and hygiene training			176.87 €				
Medical examination			82.26 €				
<b>Total chapter (99 luminaires/project)</b>			<b>886.03 €</b>				
<b>Budget of Material Execution</b>				<b>145,283.87 €</b>			

**Table 9.** Budget summary. Technical feasibility study of an APL alternative installation project.

Chapter	Summary	Amount, Reference Project	Amount, Own Project
1	Electricity	70,785.00 €	82,300.39 €
2	Civil work	182,127.46 €	62,097.45 €
3	Health and safety	3869.43 €	886.03 €
<b>Total material costs</b>		<b>256,781.89 €</b>	<b>145,283.87 €</b>
General Costs (13%)		33,381.65 €	18,886.90 €
Industrial Benefit (6%)		15,406.91 €	8717.03 €
<b>Total contract budget</b>		<b>305,570.45 €</b>	<b>172,887.81 €</b>
Taxes (7%)		21,389.93 €	12,102.15 €
<b>Total general budget</b>		<b>326,960.38 €</b>	<b>184,989.95 €</b>

Secondly, after a technical feasibility study in which a lighting installation powered by photovoltaic solar energy was dimensioned to satisfy the same requirements as the reference installation, a final budget of 184,989.95 € was determined for a total of 99 LED solar lights according to the simulations. Therefore, it can be concluded that the average price of each solar luminaire for a project of these characteristics is 1868.59 €. The summary of the budget can be analyzed in detail and compared with the previous case in Table 9.

Finally, the analysis of previous public tenders in Spanish territory describes an average cost per LED luminaire of 1875.24 €, as depicted in Table 9. Costs include foundation, installation, general expenses, industrial profit, and taxes.

The results of public tenders analyses in Spain focused on the renewal of street lighting in the last 3 years using ASL (Table 10) are compared. The three economic studies are grouped and compared in Table 11. This result is very similar to the value obtained in our specific study, as given in the previous paragraph.

**Table 10.** Public tenders in Spain related to the installation of PV street lighting (Source: own elaboration).

Place	Proposed System	N° of Luminaries	Luminaries Power	Average Price Per Luminaire
Lloseta, Balearic Islands.	Road luminaire: LED matrix, battery, regulator, and PV panel integrated in one body	39	40 W	1280.96 €
Calpe, Valencia	Road luminaire: LED matrix, battery, regulator, and PV panel integrated in one body	102	30 W	1274.51 €
Pamplona, Navarra.	Road luminaire: battery, regulator, and PV panel not integrated with the lighting system	31	30 W	3077.34 €
Málaga, Andalusia.	Road luminaire: battery, regulator, and PV panel not integrated with the lighting system	72	30 W	2470.58 €
Antigua, Las Palmas.	Road luminaire: battery, regulator, and PV panel not integrated with the lighting system	75	42 W	1581.94 €
Málaga, Andalusia.	Road luminaire: battery, regulator, and PV panel not integrated with the lighting system	38	30 W	2417.29 €
Ibiza, Balearic Islands.	Road luminaire: battery, regulator, and PV panel not integrated with the lighting system	67	30 W	2550.79 €

**Table 11.** Results of the economic viability study (Source: own elaboration).

	Energy Results			Economic Results	
	Luminaries Power	Energy Consumption	Total Installation Budget	Average Price per Luminaire	Decreased Budget
Reference installation	58.1 W	6995.78 Kwh/year	326,960.38 €	3302.63 €	0.00%
Study of public tenders	32.5 W	0.00 Kwh/year	185,648.76 €	1875.24 €	43.22%
Study of technical viability	40.0 W	0.00 Kwh/year	184,989.95 €	1868.59 €	43.42%

Overall, this analysis concluded that the use of this technology represents a saving in material execution budget of 43.42% with respect to the channeling of the alternating current grid and installation of new LED luminaires, necessary for the adaptation to the regulations of the existing aerial and surface electrical installations by the facades of the houses (reference project). This valuation was obtained using the 26th Edition of the Construction Price Base in the Canary Islands and the 5th edition of the Road Works Price

Base in the Canary Islands. In addition, the average budgets of five different projects with similar characteristics and the construction price bases of Galicia and Andalusia were compared, detecting a deviation of less than 5%.

#### 4.3. Analysis of Social Viability. Study of Citizen Perception

In the past years, several surveys have been conducted to evaluate the acceptance of the use of photovoltaic solar energy in urban environments. For example, Singh et al. [53] conducted a survey consisting of 14 questions about public opinion in reference to the use of PV energy in different regions of India. On the other hand, Chandrasekar and Kandpal [54] conducted a questionnaire to seek the opinion of different stakeholders of issues related to the dissemination of renewable energy technologies in India, concluding that the solar photovoltaic technologies reflect better societal acceptance.

Heras-Saizarbitoria et al. [55] performed an analysis of the Spanish PV solar experience, claiming that 90% of Spanish people (as opposed to 84% of Europeans) believe that renewable energy sources should be guaranteed a minimum basic quota in the energy generation mix and 50% of those interviewed consider PV solar energy as the best option.

In order to obtain public opinion of the Spanish society on the application of solar energy to public lighting in our cities, an open access online survey with 453 anonymous subjects from all the country was conducted. Only the age group and the city of residence was required before accessing the survey, which comprised 6 technical questions detailed in Figure 6. The survey was published to the population of the Engineering School of the Universidad de Málaga and to the main contacts of all the authors of this work, asking to resend freely the invitation to participate. The population was divided into four separate age groups: under 26, between 26 and 50, between 51 and 75, and older than 75 years old.

It is noteworthy that almost 60% of respondents correspond to a sector of the population with an age under 26 years old, showing a bigger interest in the topic for this age group. The main results of the study, overall, are presented in Figure 6.

More in depth, the following conclusions that can be extracted from these questionnaires are summarized in the following list:

- The four groups of age are equally aware that there is electrical wiring conducted by the facades of buildings in their cities ( $p$ -value = 0.483, Fisher's exact test). Only 5% of respondents say they are not aware of this matter.
- Almost 70% of respondents agree or totally agree to consider priority improvements in street lighting over any other action to improve the energy sustainability of your municipality. However, in this case, the differences among groups of age are significant; it has to be highlighted that 92% of 25 years old or younger subjects chose this answer, a higher proportion compared with the rest of the groups ( $p$ -value = 0.001, Fisher's exact test;  $z$ -test  $p$ -value < 0.05; under 26 vs. other groups of age).
- A total 88% of the subjects consider a sustainable and adequate solution to renew the installation of urban lighting, and that the new installation is powered exclusively by PV energy. At first glance, there are no relevant differences considering different segments of ages. From the statistical evaluation of the results, it is obtained that the opinion and age of the interviewees are independent in this question ( $p$ -value = 0.979, Fisher's exact test).
- Regarding the situation of continuous unfavorable environmental conditions, such as 4–5 days in a row with a very cloudy sky, the intensity of the lighting can be reduced up to 50% of the normal values to guarantee the service; 47% of respondents consider it problematic and 17% very problematic. Thus, although the technology is highly valued, still, the existing drawbacks originate social reluctance. In this case, people under 50 years of age significantly answered that this is problematic compared with the other two older groups of subjects ( $p$  = 0.004, Fisher's exact test;  $z$ -test  $p$ -value < 0,05 under 26 and 26 to 50 years groups vs. 51 and 75 years and older than 75 years groups).

- In reference to the visual perception of the proposed technology compared with the conventional one, 33% consider it neutral/indifferent, whereas more than 50% find the change favorable, being very favorable or favorable with 27% and 26%, respectively. No differences in the distribution of the answers between age groups were found ( $p$ -value = 0.687, Fisher's exact test).
- With regard to the possible increase in vandalism, more than half of the respondents consider that the problem of vandalism can be aggravated. As in the previous question, this is the opinion of both younger and older subjects as the differences between their answers are not significant ( $p$ -value = 0.418, Fisher's exact test).
- The number of answers choosing the option "Do not Know" was extremely low. Only questions 4 and 6 have reached 3% and 4% of cases, respectively, being lower or null in the other cases. Thus, it can be regarded as a topic of interest or relevant for the studied population.

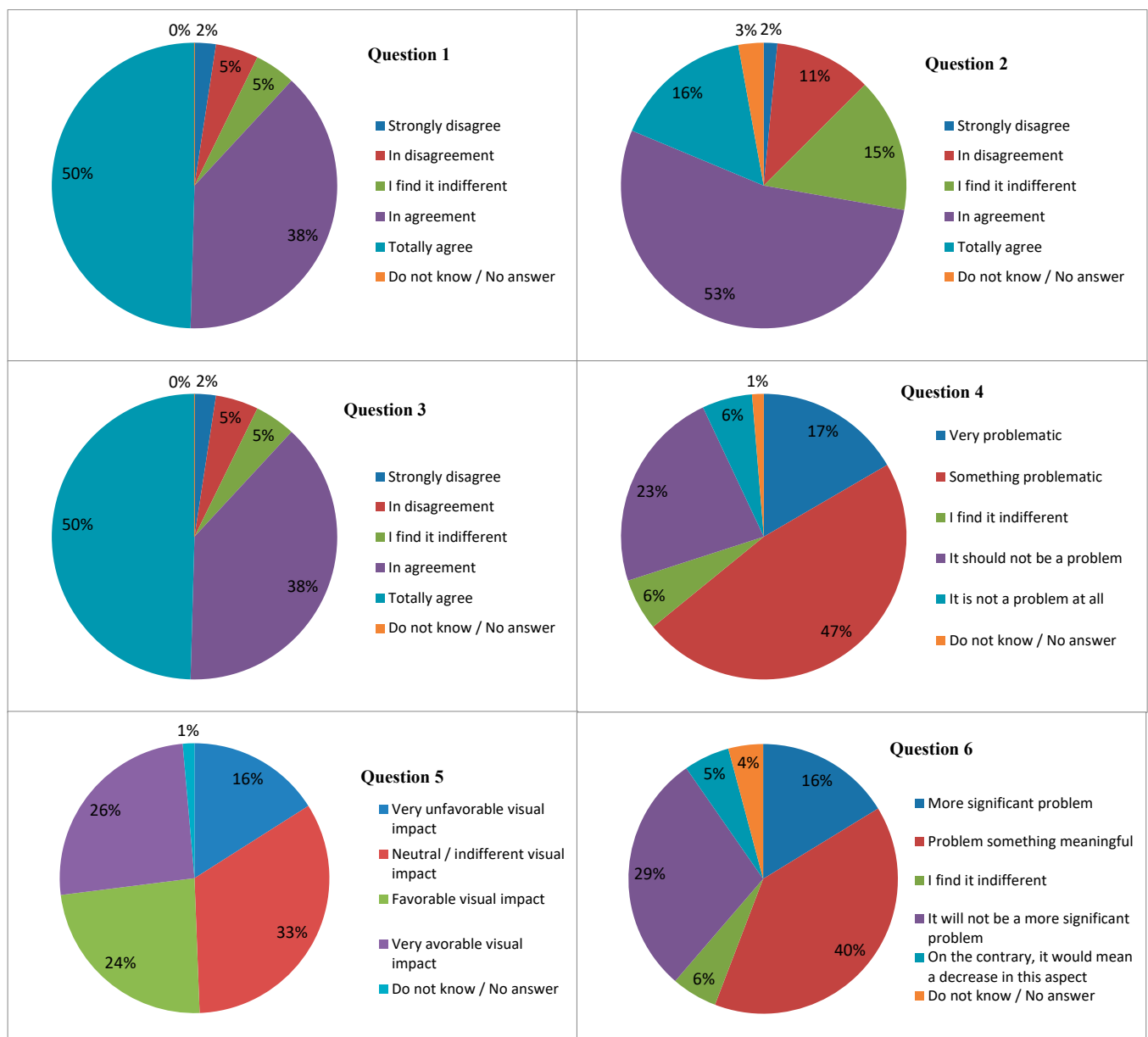


Figure 6. Summary of the statistical study of the social perception of PV urban lighting.

**Question 1:** Are you aware that there is electrical wiring conducted by the facades of buildings and homes in your municipality?

**Question 2:** Among the possible actions to be taken to improve the energy sustainability of your municipality, do you consider it a priority to make improvements in public lighting above any other type of action?

**Question 3:** Do you value as a sustainable and adequate solution that the installation of urban street lighting is renewed so that it is exclusively powered by solar energy?

**Question 4:** How problematic do you think that, under unfavorable environmental conditions, such as 4–5 consecutive days with a very cloudy sky, the intensity of the lighting can decrease up to 50% of the normal values?

**Question 5:** How do you consider the visual impact that the installation of this type of luminaires would generate in your municipality with respect to the existing models?

**Question 6:** Do you consider that vandalism can be a more significant problem with this type of solar luminaires than with those currently existing in your municipality?

## 5. Conclusions

Nowadays, the generalization of LED luminaires has meant a new technological revolution within this segment of products.

PV LED lighting installations are now positioned as an efficient technology and an economically viable option to cover the needs of street lighting inside cities. This is based on the increase in the costs of electricity and fossil fuels [56], the exponential decrease in the price of Watt-peak (Wp) generated with PV panels [57], and the consistent increase in efficiency of LED emitters. This approach is not just for projects in which they are the only viable option (places without access to electricity), but also for the renewal of urban public lighting, where the luminaires with AC power supply had no competition to date [58]. Such a fact has special relevance in areas with very aged or deteriorated electrical installations. Here, it has been avoided to replace or adapt the facilities to the current regulations, saving very significant costs such as underground channeling [59,60].

The authors of the presented research conclude that urban photovoltaic public lighting installations are technically, economically, and socially viable by virtue of the results obtained.

The technical feasibility analysis, carried out in the context of a practical case, allows us to visualize the installation and verify that the proposed technology fulfills the regulatory requirements. This study is contrasted with the analysis of public tenders in Spain, where it is verified how LED solar luminaires begin to obtain prominence in recent years.

On the other hand, the economic feasibility study provides the most significant results, determining that it is 44% more viable to carry out a PV LED lighting installation with respect to an LED lighting installation connected to the alternating current grid and adapted to the current regulations through underground channeling.

Finally, from the study of social viability, it is concluded that the majority of the population is aware of the problem in the conduction of electricity and, in turn, 89% consider it a sustainable and adequate solution that the lighting installation is renewed being supplied exclusively by photovoltaic solar energy. Besides, most of the respondents value as problematic the fact that under continued unfavorable environmental conditions, the intensity of the lighting can be lowered to guarantee the service, and more than half consider that the problem of vandalism can be aggravated.

The environmental demands, the growing international commitment to the use of renewable energy sources, and the proven viability of LED PV lighting technology have led to encouraging forecasts in favor of this technology, awaiting its progressive implementation in areas with suitable solar resources.

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